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THERMAL RESPONSES AND EFFICIENCY OF SWEATING WHEN MEN ARE DRESSED IN ARCTIC CLOTHING AND EXPOSED TO EXTREME COLD[1]

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Men experienced in living out of doors in extremely cold weather emphasize the great importance of "under dressing" during periods of muscular activity in order to avoid accumulation of sweat in the clothing (e.g., Siple, 1945). However, it seems to be true that even when the greatest care is taken moisture may accumulate in quantities large enough to endanger survival if exposure is prolonged. Cherry-Gerard (1922) of Scott's polar expedition said:

> I never knew before how much of the body's waste comes out through the pores of the skin. On the most bitter days . . . it seemed that we must be sweating. And all of this sweat, instead of passing away through the porous wool of our clothing and drying off us, froze and accumulated. It passed just away from our flesh and then became ice . . . . But when we got into our sleeping bags, if we were fortunate, we became warm enough during the night to thaw this ice: part remained in our clothes, part passed into the skins of our sleeping bags, and soon both were sheets of armour-plate.

Laboratory findings during prolonged tests of uniforms designed for use by the Armed Forces have been consistent with such reports as that of Cherry-Gerard. Furthermore early war experience of the U. S. Army resulted in establishment of special facilities for drying clothing that had been worn in frigid weather either on the ground or in heavy bombardment aircraft at high altitude.

Such observations as these led us to investigate the factors involved in heat balance for men exposed to extreme cold, with particular reference to the part played by the sweating mechanism. The present study is concerned with *a*, amount of sweating; *b*, efficiency of the sweat for body cooling; and *c*, the relationships between sweating on the one hand and skin temperature, internal temperature, and comfort on the other when men are heavily dressed. To obtain a better understanding of the principles involved the environmental temperature and grade of activity have been varied within wide limits.

METHODS. The procedures were designed to provide information on amount of sweating, amount of moisture taken up or lost by the clothing, effectiveness

[1] This work was started under a contract recommended by the Committee on Medical Research, between the Office of Scientific Research and Development and the President and Fellows of Harvard College; it was finished under a contract recommended by the Committee on Quartermaster Problems, between the National Academy of Sciences and the President and Fellows of Harvard College.

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of the sweat for body cooling, energy production, heart rate, internal and skin temperatures and thermal sensation.

Most of the experiments were performed on two young men selected from a larger group because in preliminary trials they did not represent extremes in regard to their sweating response during work and because they were physically fit to perform fairly hard muscular work. The height, weight and surface area of the men were:

Subject	*Ht. (cm.)*	*Weight (kgm.)*	*Surface Area (sq. m.)*
G. S.	176	61–63	1.76
J. S.	178	72–74	1.90

In each experiment the amount of sweating was determined by weighing the subject nude and also fully dressed before and after each exposure. Weighings were to the nearest gram on a Sauter balance. To minimize the known effects of dehydration in reducing sweating (Pitts, Johnson and Consolazio, 1944) the subjects drank 500 cc. of water before the first weighing. The sweat secreted during the actual exposure was computed as (nude weight loss) minus (weight lost through the lungs) minus (weight lost during the dressing and undressing periods).

The weight lost from the lungs included water vapor and excess weight of the CO_2 expired over the O_2 inspired. Calculation of the former was based on the assumption that the expired air was at 91°F. and saturated at a cost of 0.035 grams of body water for each liter of air expired when the ambient temperature was 20° F. and lower, and at a cost of 0.029 gram at an ambient temperature of 40°F. The excess weight, in grams, of the CO_2 expired was calculated assuming an R.Q. of 0.88 by multiplying the oxygen consumption in liters/hr. STP dry by 0.3.

Dressing took about 35 minutes and undressing about 5 minutes. All items except the heavy parkas were put on in a warm room. The final garments were donned in the cool lock outside the cold room while the rectal temperatures and initial skin temperatures were being determined. In an effort to avoid sweating during the dressing period an assistant was provided to aid in the process. The weight loss of the subject during the dressing and undressing periods was calculated to be (nude weight loss) minus (weight loss clothed) minus (moisture gain of clothing). This method of computation was validated by control experiments in which all procedures were the same except that the subject never entered the cold room. These control experiments also provided evidence that the weight change of the clothing itself during dressing and undressing is negligible. After extensive experience with these methods, we estimate that the values obtained for sweating and for total moisture uptake of the clothing during the exposures are usually within 25 grams of the true values.

Energy production in Calories was considered to be 4.9 times oxygen consumption in liters STP dry. During sitting and standing experiments, a continuous record of oxygen consumption and ventilation was obtained by means of a closed circuit apparatus using a 100 liter Tissot gasometer as the oxygen reservoir. During the walking experiments oxygen consumption and ventilation were measured for five-minute periods half-way through both the first and second hours using an open-circuit apparatus; these measurements checked so closely that the average of the two was considered representative of the entire period of exposure.

The heart rate was determined each half hour by palpation of the radial artery.

Rectal temperature was determined with a clinical thermometer at the beginning and after 60 and 120 minutes of exposure. Skin temperature was determined at 10 locations with copper-constantan thermocouples and a potentiometer. Each couple was read every 15 minutes and the values obtained from individual couples were appropriately weighted when determining mean skin temperature. However, no couple was located on the exposed portion of the

TABLE 1

Components of the Arctic Uniform, with weights

	WEIGHT
	gms.
Shorts, cotton	120
Undershirt, 50% wool, 50% cotton	370
Drawers, 50% wool, 50% cotton	320
Socks, cushion sole	80
Shirt, flannel, O.D.	515
Trousers, wool, O.D.	1055
Mittens, wool, insert	115
Socks, ski	250
Parka, pile, M-1944	1355
Parka, cotton, M-1944	1100
Trousers, cotton, field, M-1944	765
Mittens, shell	195
Shoes, felt, with felt insoles	1310
Total	7550

face, which represented about 4 per cent of the total surface of the body. Each item of clothing was weighed to the nearest gram before and after use.

The following standard or experimental U. S. Quartermaster items made up the 17-pound clothing assembly used in this study and hereafter referred to as the "Arctic Uniform" are listed in table 1. This uniform is adequate to protect men who are moderately active at about 0°F. In the conventional units of insulation used for clothing it would be rated at about 3.0 Clos (Siple, 1945).

It is known that pre-dried clothing adsorbs a good deal of moisture from the air when placed in our cold chamber, and theoretically a fraction of the heat given off in the adsorption would be effective for warming the skin.[4] Therefore

[4] Attempts have been made to measure the heat of condensation plus heat of hydration by several workers with results varying between 0.5 and 2.0 Cals./gram for textile yarns (cf. Darling and Belding, 1946).

to reduce adsorption to a reasonable level and to assure some uniformity of adsorption in similar exposures of men in the cold room the clothing was preconditioned overnight or longer in a room at 95°F., 50 per cent relative humidity. Initial weight of the individual garments then varied by less than 2 per cent from day to day. Under these conditions it may be assumed that the moisture content of the wool in the garments was about 13 per cent, of the cotton about 9 per cent of dry weight (Wiegerinck, 1940). The data of Darling and Belding (1946) indicate that maximum adsorption in the cold room would probably not exceed 22 per cent for wool and 11 or 12 per cent for cotton, and that even these values would not be applicable for the garments close to the skin because they would be relatively warm. Assuming an average adsorption of 18 per cent as maximum for the 7550 grams, part wool, part cotton Arctic Uniform while worn in the cold room, and assuming an initial moisture content averaging 11 per cent the total adsorption of sweat and environmental moisture might amount to as much as 50 grams during an exposure. Had the clothing been dried in an oven before use adsorption might have reached 130 grams.

The two principal variables, namely, amount of activity and environmental temperature, have been investigated separately.

In studies of the effects of amount of activity the environmental temperature was maintained at 0°F. In separate exposures the subjects sat, stood quietly, walked at five different speeds on the level, and climbed at 3.5 miles per hour up several grades, the steepest of which was 12.0 per cent. (Here the "grade" is the height climbed expressed as a percentage of the distance walked.)

Two separate sets of experiments were performed to determine the effects of environmental temperature. In one set the work performed was constant, a walk at 3.5 miles per hour up a 6.5 per cent grade; in the other, the work was adjusted to give the same rate of sweating at three environmental temperatures so that the effect of temperature on the fate of the sweat might be estimated.

The environmental conditions were these:

Temperature °F.	*Relative humidity* %
40 ± 2	85 ± 5 (ref. water)
0 ± 2	86 ± 3 (ref. ice)
−20 ± 2	100 (ref. ice)
−40 ± 2	100 (ref. ice)

Wall temperature = ambient temperature within ±2°
Wind: turbulent, continuous, about 2 m.p.h.

RESULTS AND DISCUSSION. *Inter- and intra-individual variability.* Before selecting the two subjects for intensive studies, experiments were performed with six different men under identical conditions to determine what variability might be encountered among subjects. The most striking result of this study (table 2) was the demonstration that the sweating of two men may differ by as much as 100 per cent. Subject R. W. sweated only 708 grams in two hours under conditions which evoked secretion of 1457 grams by S. C. This great difference in activity of the sweating mechanism of different individuals awaits explanation. As might be expected moisture uptake of the clothing was closely correlated with sweat production. The variability of the other data is smaller but nevertheless meaningful. Energy production varied by as much as 50 Cals./m²/hr. (a 17 per cent difference as compared with an even greater maximum difference of 24 per cent when metabolism was expressed on a unit body weight basis). The low mean skin temperature observed on P. K. was 4°F. less than that observed on any other man and 7°F. less than the highest. Final rectal temperatures differed in the extreme by 1.2°F., a significant amount considering that the average variability for any individual did not exceed 0.3°F.

There is an obvious, though not perfect, inter-correlation among some of these data. A higher rate of sweat secretion was usually accompanied by higher average skin and rectal temperatures, a greater heat production per unit surface area and a larger retention of moisture in the clothing.

TABLE 2

Inter-individual variability. Average results of two-hour exposures of six subjects at 0°F. They walked at 3.5 miles per hour up a 6.5 per cent grade while dressed in an Arctic Uniform

SUBJECT	NO. EXPTS.	INITIAL NUDE WT.	SURFACE AREA	SWEAT	MOISTURE UPTAKE OF CLOTHING	ENERGY PRODUCTION	RECTAL TEMPERATURE Initial	RECTAL TEMPERATURE After 1 hr.	RECTAL TEMPERATURE Final	FINAL SKIN TEMPERATURE
		kgm.	*m²*	*gms.*	*gms.*	*Cals./m²/hr.*	*°F.*	*°F.*	*°F.*	*°F.*
S. C.	4	77.8	1.92	1457	1219	324	99.2	101.7	101.7	90.3
G. S.	7	62.2	1.77	991	797	316	98.7	100.8	100.9	88.8
P. K.	5	76.2	1.95	811	650	277	99.2	100.8	101.0	83.0
J. E.	2	68.5	1.76	742	588	328	100.0	101.6	101.6	87.5
J. S.	7	72.4	1.88	722	599	304	98.5	100.6	100.5	87.9
R. W.	3	65.9	1.79	708	589	288	99.4	100.3	100.5	87.6

The two subjects used for intensive study were dissimilar in their production of sweat, 991 and 722 grams under the conditions of comparison above, but did not represent the extremes found among the six men. Precautions were taken to insure constancy of the state of health and training of these two subjects with results which can best be judged from a simple statistical analysis of the week to to week variability in their performance of the same task during the first four months of 1945 (table 3). For each of these subjects sweat secretion and moisture uptake of the clothing, although closely correlated with each other, varied much more than other measurements. Apparently in one experiment out of three under these conditions sweating may be expected to deviate from the average values by as much as 100–150 grams in two hours. Although the subjects were trained to perform this hard work before these expriments were initiated there was some tendency for sweating, heat production and skin temperature (but not rectal temperature) to fall off slightly over this period of time. For example, average sweating of G. S. in the first three as compared with the last three experiments was respectively 1027 and 871 grams and of J. S. was 762 and 706 grams; heat production of G. S. was 322 and 316 Cals./m²/hr., and of

J. S. was 309 and 299; and final mean skin temperature of G. S. was 90.4° and 87.2°F., and of J. S. was 90.8° and 86.8°F. The evidence is insufficient to decide whether these were effects of continued training, or of acclimatization to work in this environment, or of thinning of the clothing due to wear.

TABLE 3

Week-to-week variability. Results of seven two-hour exposures of each of the two principal subjects at 0°F. They walked at 3.5 miles per hour up a 6.5 per cent grade while dressed in an Arctic Uniform

CATEGORY OF COMPARISON	SUBJECT	RANGE	MEAN	COEFFICIENT OF VARIATION, %*
Sweat (gms./2 hrs.)	J. S.	620–845	722	10.4
	G. S.	818–1139	991	11.9
Moisture uptake of clothing (gms./2 hrs.)	J. S.	523–709	599	12.6
	G. S.	648–944	797	13.6
Energy production (Cals./m²/hr.)	J. S.	297–310	304	1.7
	G. S.	295–329	316	3.0
Pulse rate at 2 hrs. (beats/min.)	J. S.	124–132	129	2.6
	G. S.	132–144	138	1.7
Rectal temp. (°F.) initial	J. S.	98.3–98.7	98.5	0.2
	G. S.	98.3–99.0	98.7	0.1
1 hour	J. S.	100.3–100.9	100.6	0.2
	G. S.	100.4–101.1	100.8	0.1
2 hour	J. S.	100.1–101.0	100.6	0.1
	G. S.	100.8–101.2	100.9	0.1
Skin temp. at 2 hours (°F.)	J. S.	85.6–91.0	87.9	2.5
	G. S.	86.6–91.4	88.8	2.0
Initial nude wt. (kgm.)	J. S.	71.1–74.1	72.4	1.5
	G. S.	61.2–62.9	62.2	0.9

* Coefficient of variation $= \frac{\text{Standard Deviation}}{\text{Mean}} \times 100.$

Physiological effects of varying activity. Most of the data obtained in experiments in which the grade of activity was varied while the two subjects wore an Arctic Uniform at 0°F. are summarized in table 4.

Curves have been fitted in figures 1 and 2 to represent sweating as a function of energy production. The curves for the two men are of similar form, with an initial flat portion showing sweat secretion at a rate of 50 to 75 grams for the two hours at levels of energy production below about 175 Cals./m²/hr.; this may be regarded as insensible perspiration, not necessarily involving activity of the sweat glands. As energy production is increased from 175 to about 250 Cals./m²-/hr. thermal sweating appears, while above 250 and up to about 400 Cals./m²/hr. sweating is very nearly a linear function of energy production. It is interesting that despite the fact that G. S. had a smaller surface area he consistently sweated more than J. S.; his rectal temperature also averaged 0.3°F. higher at comparable

TABLE 4

Effects of performing various grades of activity for a two-hour period in an Arctic Uniform at 0°F.

NO. EXPTS.	ACTIVITY OR SPEED	GRADE	HEAT PRODUCTION	VENTILATION	SWEAT	MOISTURE TAKEN UP BY CLOTHING	EFFECTIVE SWEAT		FINAL MEAN SKIN TEMP	RECTAL TEMP. Initial	RECTAL TEMP. Final	COMFORT
	m.p.h.	%	*Cals./m²/hr.*	*L./hr. S.T.P.*	*gms./2 hrs.*	*gms./2 hrs.*	*gms./2 hrs.*	%	°*F.*	°*F.*	°*F.*	
Subject G. S. (surface area 1.76 m²)												
1	Sit		53	318	8	62	−17		83.6	98.6	97.6	Cold
1	Stand		63	424	71	36	65	92	79.2	99.7	97.8	Cool, feet and hands cold
1	1.29	0	110	519	76	98	36	47	85.0	98.7	98.1	Cool
1	1.80	0	123	578	96	86	62	65	85.5	98.6	99.2	Cool
1	2.25	0	146	727	59	47	44	75	83.0	98.4	99.2	Comfortable
1	3.0	0	167	806	258	188	160	62	84.5	99.0	99.4	Comfortable
3	3.5	0	208	943	253	216	137	54	85.1	99.0	99.7	Comfortable
1	3.5	2.75	238	1088	341	244	196	58	88.5	98.7	100.1	Comfortable
1	3.5	3.25	241	1051	444	309	255	57	87.1	98.9	99.9	Comfortable
1	3.5	3.75	264	1072	515	413	230	45	87.8	98.7	99.9	Warm
1	3.5	4.50	260	1049	574	424	297	52	87.4	98.7	100.3	Warm
7	3.5	6.50	316	1393	991	797	439	44	88.8	98.7	100.9	Hot
2	3.5	9.75	364	1534	1466	1206	569	39	90.6	98.7	101.2	Hot
1	3.5	12.00	426	1787	1892	1535	729	39	88.9	99.0	102.4	Very hot
Subject J. S. (surface area 1.90 m²)												
1	Sit		59	528	48	37	44	92	76.1	98.6	98.0	Cold
1	Stand		72	870	67	63	39	58	80.5	98.7	98.0	Cold
1	1.29	0	112	853	91	107	42	46	81.3	98.6	99.1	Cool, hands cold
1	1.80	0	137	972	70	78	40	57	84.0	98.6	99.1	Cool, hands cold
1	2.25	0	145	1098	33	33	29	88	82.5	98.4	98.9	Cool, hands cold
1	3.0	0	173	1366	62	66	39	63	81.9	98.1	99.3	Comfortable, hands cold
3	3.5	0	189	1496	136	134	73	54	82.4	98.4	98.9	Comfortable, hands cool
1	3.5	2.50	216	1694	173	191	67	39	86.7	98.3	99.3	Comfortable
1	3.5	3.00	227	1797	244	225	111	45	85.8	98.2	99.7	Comfortable
1	3.5	3.25	228	1693	306	230	170	56	88.0	98.4	99.9	Warm
1	3.5	4.50	262	1808	446	347	227	51	87.1	98.3	100.1	Warm
7	3.5	6.50	304	2313	722	599	320	44	88.0	98.5	100.5	Hot
2	3.5	9.75	371	2726	1299	1126	472	36	91.1	98.3	101.1	Hot

levels of energy production, but his skin temperature was not shown to be significantly different from that of J. S.

Sweating as a function of metabolism might be expected to follow a sigmoid curve. The characteristic lower curved segment and a long ascending limb are present, but the upper flattened portion associated with maximum capacity of the sweat glands to produce is missing. Data of Robinson, Turrell and Gerking (1945) showing sweating and the values of other factors associated with very

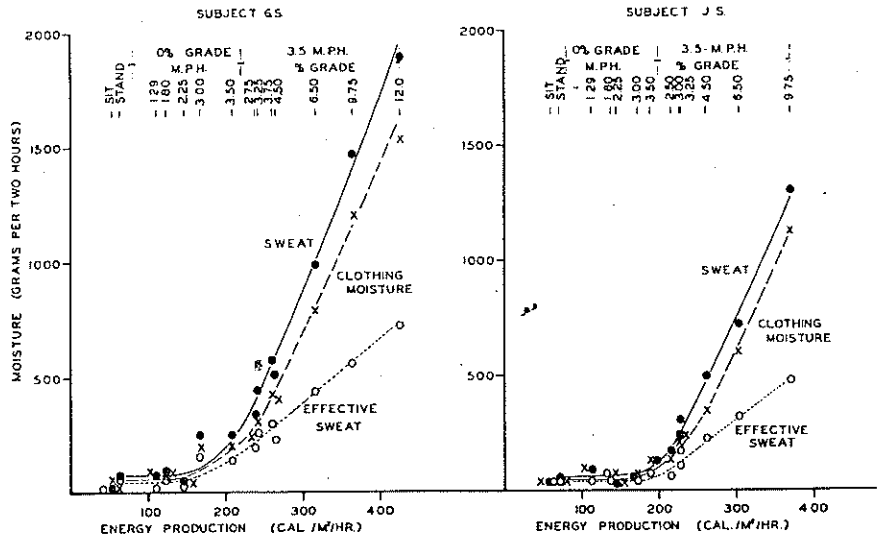

Fig. 1. Total sweat, moisture retention in clothing and effective sweat for cooling plotted as functions of energy production. The subjects sat, stood or walked at various speeds and grades at an environmental temperature of 0°F. while wearing the Arctic Uniform.

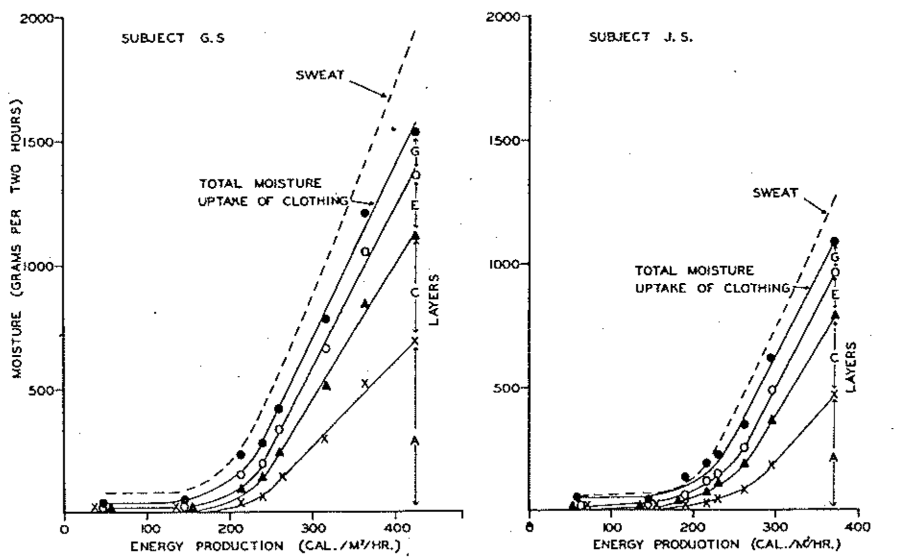

Fig. 2. Total sweat and moisture retention in the layers of clothing plotted as functions of energy production. The subjects sat, stood or walked at various speeds and grades at an environmental temperature of 0°F. while wearing the Arctic Uniform.

severe heat stress in hot environments are compared in table 5 with our data obtained during the most strenuous walk of G. S. at 0°F. to demonstrate that thermal stress as judged from the relatively low final skin and rectal temperatures in our experiments was insufficient to evoke a maximal output of sweat. It is also interesting that when Robinson et al. observed rates of sweat production similar to ours (bottom of table 5) the skin temperatures of their men were generally higher and rectal temperatures were considerably lower.

Our data show that metabolism and thermal sweating may be linearly related when the clothing and environmental temperature are held constant, but what do they show about the relationship between sweating, skin and rectal temperatures and comfort? These also are correlated in a systematic fashion. With activity such that sweating was at an insensible level, final mean skin temperature was 85°F. or less, final rectal temperature was 99.3°F. or less, and comfort varied from

TABLE 5

Data selected from Robinson, Turrell and Gerking (1945) for comparison of responses in light clothing in the heat with those of our subject G. S. working very hard in Arctic Clothing at 0°F.

	ACTIVITY	METABOLISM	SWEAT	RECTAL TEMP.	SKIN TEMP.	PULSE RATE
		Cals./m²/hr.	*gms./hr.*	*°F.*	*°F.*	*beats/min.*
Greatest tolerable stress; Robinson's data, wearing light clothing in the heat	Walking at 3.5 m.p.h. up a 2.5% grade	about 189	about 2000	about 104.7	about 101	about 170
Our data on G. S. in Arctic Clothing; subject "very hot"	Walking at 3.5 m.p.h. up a 12.0% grade	426	946	102.4	89	172
Sweating approximately 946 gm./hr. Mean of 4 expts. of Robinson; light clothing in heat	Walking at 3.5 m.p.h. up a 2.5% grade	about 189	980	99.9	93	105

"cold" in the sitting and standing experiments to "comfortable" at the highest levels of activity which failed to evoke thermal sweating. At metabolic levels between 175 and 250 Cals./m²/hr. where sweating is a curvilinear function of metabolism, mean skin temperatures ranged between 82° and 87°F., rectal temperatures between 99.3° and 100.0°F., and the men judged themselves to be "comfortable." When metabolism was raised above 250 Cals./m²/hr. mean skin temperatures rose from 88° to 91°F., rectal temperatures from 100.0° to 102.4°F. and comfort ranged from "warm" through "hot" to "very hot". It appears that all of these data are mutually intercorrelated and in the positive sense.

Are thermal comfort sensations to be relied on when men wish to keep sweating at a minimum in the cold? At 0°F. had our men been instructed to maintain their activity at a level at which they felt "cool but comfortable" thermal sweating would have been avoided. But with other uniforms and at different environmental temperatures if we recommend "underdressing" for each activity to the point of feeling "cool" will thermal sweating likewise be avoided? Also, is the sensation "comfortable" always to be associated with a mean skin temperature between 82° and 87°F. when men are working moderately hard, or do these values apply only when men are working under the particular set of conditions applicable here? We do know that when men are sitting quietly in a temperate environment and are "comfortable" average skin temperature usually lies between 92° and 94°F.

Physiological effects at different environmental temperatures. Limited information is available concerning the effects of performing a standard grade of hard work at different temperatures (table 6). The Arctic Uniform that was "hot" for J. S. while working at 0°F. was "comfortable" during the same work at −40°F. When environmental temperature was reduced by 40°F. average

TABLE 6

Average effects of walking at 3.5 miles per hour up a 6.5 per cent grade in an Arctic Uniform at three environmental temperatures

Subject J. S.; surface area 1.90 square meters; exposure period 2 hours.

NO. EXPTS.	ROOM TEMP.	METABOLISM	SWEAT	MOISTURE TAKEN UP BY CLOTHING		EFFECTIVE SWEAT		FINAL SKIN TEMP.	RECTAL TEMP.		COMFORT
									Initial	Final	
	°F.	Cals./m²/hr.	gms./2 hr.	gms./2 hr.	% of sweat	gms./2 hr.	% of sweat	°F.	°F.	°F.	
7	0	304	722	599	83	320	44	88	98.5	100.5	hot
1	−20	316	659	607	92	284	43	82	98.8	100.5	warm
2	−40	317	179	190	106	70	39	81	98.5	100.2	comf.

skin temperature decreased from 88° to 81°F. and sweating from 722 to 179 grams in twohours; however, final rectal temperature fell only 0.3°F. At −40°F. the amount of sweat secreted was about equivalent to that secreted at 0°F. at a level of activity involving 100 Cals./m²/hr. less energy expenditure (cf. table 4).

When activity was modified in a way to produce approximately equal production of sweat at 3 different environmental temperatures (table 7) the difference in energy production (between 40° and 0°F.) required was again of the order of 100 Cals./m²/hr. This study also revealed that at lower environmental temperatures equivalent sweating is accompanied by lower skin temperature and somewhat higher rectal temperature. In other words, rectal temperature, despite the lower environmental temperature associated with greater work, was positively correlated with metabolism, whereas skin temperature was positively correlated with environmental temperature.

Fate of the sweat; moisture uptake of clothing. Most of the sweat secreted by the subjects while wearing an Arctic Uniform was retained in their clothing under all conditions of use reported here. Admittedly these were brief exposures, but evidence exists from the results of a five-day continuous exposure of two men at 0°F. in our cold room and from Arctic experience, that the intermediate and outer layers of clothing accumulate increasing amounts of moisture if given prolonged use where it is not possible to use a fire for drying; on the other hand even when profuse sweating results in wetting of the underclothing during work it rapidly dries afterward.

We seek an explanation both for the observed moisture uptake of the garments in these experiments and the experience with continued use. The amount of evaporation occurring from any surface is primarily dependent on the vapor pressure gradient between the surface and its immediate environment and secondarily a function a, of air movement (which in turn is dependent on the shape of the exposed surface as well as wind velocity), and b, the vapor resistance offered

TABLE 7

Results of single experiments at different temperatures under conditions of activity that resulted in similar sweating

CATEGORY OF COMPARISON	SWEAT 732 TO 1016 GMS./2 HRS.						SWEAT 403 TO 471 GMS./2 HRS.					
	Subject J. S.			Subject G. S.			Subject J. S.			Subject G. S.		
Room temp. (°F.)	+40	0	−20	+40	0	−20	+40	0	−20	+40	0	−20
Speed (m.p.h.)	3.5	3.5	3.5	3.5	3.5	3.5	3.0	3.5	3.5	2.3	3.5	3.5
Grade (%)	1.0	6.5	8.0	1.0	6.5	6.5	0	4.5	5.0	0	3.3	4.5
Energy production (Cals./-Kgm./hr.)	214	316	354	228	312	332	163	262	283	145	241	269
Final mean skin temp. (°F.)	92.1	86.1	82.6	91.7	85.2	82.7	91.3	87.4	82.9	92.3	85.6	81.6
Final rectal temp. (°F.)	99.6	100.7	101.3	100.2	100.9	100.6	99.4	100.1	100.1	99.6	99.9	100.2
Sweat (gms./2 hrs.)	760	732	754	928	968	1016	471	446	403	443	444	471
Per cent of sweat taken up by clothing	66	88	96	68	82	87	67	78	71	62	70	89
Per cent of sweat in each layer of clothing												
Layer A	17	22	24	28	28	28	11	18	−4	17	15	13
Layer C	19	27	30	19	23	26	19	24	25	17	20	28
Layer E	13	20	23	12	17	19	15	16	23	12	16	25
Layer G	17	19	19	9	14	14	22	20	27	16	20	23
Effective sweat (gms./2 hrs.)	410	317	247	464	417	407	251	228	185	267	252	227
(per cent of sweat)	58	43	33	50	43	40	53	51	46	60	57	48
Comfort	Comf.	Hot	Warm	Warm	Warm	Warm	Comf.	Warm	Warm	Comf.	Comf.	Comf.

by any materials placed between the wet surface and the environment. The principles governing evaporation of moisture from the skin of clothed men in temperate and hot environments have received some attention (e.g., Burton, 1944) but hitherto only casual observations have been made in regard to moisture transfer from the skin in cold environments where the vapor pressure gradient is large and the clothing is thick and heavy. We are aided in our discussion of this topic by the study of Fourt, Fisk, Parrish and Harris (1945) of the transfer of vapor from the wetted "skin" of a cylinder through clothing to the environment, and by the study of Tucker, Goodings and Kitching (1944) of the permeability of textile materials to water vapor.

Here we wish to estimate the amount of evaporation that might be expected with the temperature gradient that existed in most of our experiments. Tucker et al. have provided physiologists with a convenient formula which may be used for this purpose. Let W equal grams of water evaporated/m²/hr. Let F be a factor which expresses the vapor transfer in grams/m²/hr. for a thickness of dead air equal to 1 cm. when the difference in vapor pressure is 1 mm. Hg. This factor varies with air temperature, from 8.35 at 0°C. to 8.97 at 30°C.; we have arbitrarily selected 8.4 as being applicable for our rough calculations. W is readily obtained by multiplying F by $\Delta V.P.$, the differences in vapor pressure, and dividing by the thickness of dead air, R, with which we are concerned:

$$W = \frac{F}{R} \times \Delta V.P.$$

The vapor pressure and moisture-holding capacity of saturated air are plotted as functions of environmental temperature in figure 3.

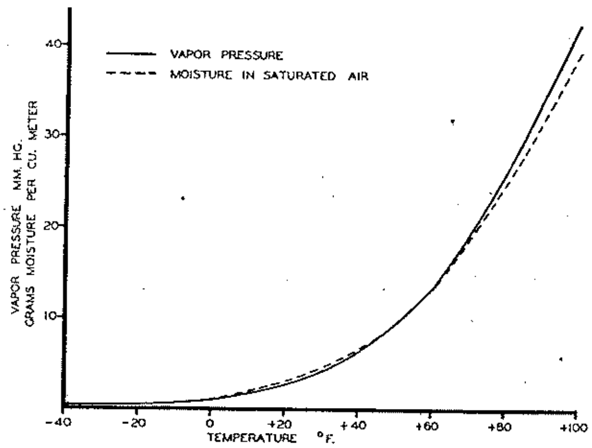

Fig. 3. The relationship of vapor pressure to moisture in saturated air at temperatures ranging from −40°F. to +100°F.

We first consider a hypothetical situation: with a completely wet skin at 93°F. V.P. = 40 mm. Hg) in an environment at 0°F. with 100 per cent relative humidity (V. P. = 1 mm. Hg) and with a 2-mile per hour wind blowing how much evaporation will occur? Using figures of Burton we have calculated that at this wind velocity the resistance provided by the relatively immobile air close to the skin is equivalent to about 0.23 cm. of dead air[5] (it would be about 0.46 cm. in a room with no perceptible wind). Then

$$W = \frac{8.4}{0.23} \times 39 = 1410 \text{ g/m}^2\text{/hr.}$$

[5] Calculated as follows: the insulation of 1 cm. of dead air is about 1.85 Clos (Burton, 1942); effective insulation with air movement at 2 m.p.h. is about 0.43 Clo (Burton, 1945); therefore 0.43:R::1.85:1, and R is 0.23, R being the resistance expressed as an equivalent thickness of dead air.

This is about 3 times the rate of sweat secretion observed in any of our experiments.

If we now interpose the Arctic Uniform in this system the potentialities for evaporation are reduced *a*, because the effective resistance of dead air has been increased and *b*, because the fabrics offer an additional specific resistance to vapor transfer. It will be shown in an accompanying paper that the effective resistance to heat flow by convection and radiation when walking at 3.5 miles per hour is about 1.7 Clo units, and since 1.85 Clos are provided by a layer of dead air 1 cm. thick the effective thickness of dead air in this case is 0.92 cm. We now consider the data of Tucker et al. regarding the specific resistance to moisture transfer of various fabrics; that of underwear is about 2.2 × the dead air effective for thermal insulation, of worsted serge 2.1, of double pile cloth 1.0 and of cotton poplin 2.3. Let us take the value of 2.0 as the average specific resistance of the uniform; then 2 × 0.92 = 1.8 cm., and

$$W = \frac{8.4}{1.8} \times 39 = 180 \text{ g/m}^2\text{/hr.}$$

Thus the presence of the uniform might be considered to have reduced the potentialities for evaporation from a completely wet skin by more than 80 per cent. Both values for W so far obtained are probably too low because the body is made up of a series of cylinders, while the figures of Tucker et al. apply for horizontal plane surfaces from which evaporation occurs at a lower rate.

From the above approximations we might predict that subject J. S., who sweated about 193 grams/m²/hr. during a walk up a 6.5 per cent grade at 3.5 m.p.h. would evaporate about all of his sweat to the ambient air when in fact 157 grams/m²/hr. (81 per cent of his sweat) were retained in his clothing. Even when sweating occurred at the low rate of 60 grams/m²/hr. during a walk on the level as much as 50 grams/m²/hr. remained in the clothing.

Why does not the above prediction regarding over-all vapor transfer through the clothing apply? We believe it is because the air temperature in the clothing drops below the dew point and because the clothing provides, from within outward, a series of progressively cooler "screens" upon which condensation readily occurs. We have therefore formulated a hypothesis regarding behaviour of moisture for clothed subjects which takes into consideration the vapor pressure gradient from layer to layer in the system rather than the over-all gradient from skin to ambient air. According to this hypothesis *a*, the vapor pressure of a layer may not exceed that of saturation at the existing temperature of the layer; and *b*, the potential transfer of moisture between contiguous layers is dependent on the vapor pressure difference between the layers.

With the data at hand our hypothesis may be tested in several ways. As a preliminary test we determined with thermocouples the actual temperatures of the layers of clothing over the trunk and arms when subjects were exposed at 0°F. and walking at 3.5 miles per hour. These were found to be about the same regardless of the amount of sweating and the steepness of the climb, and the values obtained have been set down in table 2 together with other data which make it possible roughly to predict the retention of moisture in the layers of the Arctic Uniform at three levels of sweat production. These predictions are based on the assumption that the resistance to vapor transfer presented by each of the five layers is equal and that the sum is the 1.8 cm. given above.

$$\text{Then } W = \frac{8.4}{0.36} \times \Delta V.P. = \text{grams evaporated from layer/m}^2\text{/hr.}$$

Since one square meter is roughly the surface of the regions covered by these garments (trunk, hips, arms and head) the figures in column 4 of table 8 represent the maximum evaporative transfer to be expected through these garments. At any point in the system moisture in excess of what can be passed to the next

TABLE 8

Temperatures and assumed maximum vapor pressures in layers of the Arctic Uniform with predicted and actual uptake of moisture by the layers while walking at 3.5 miles per hour. See text for description of method used in making predictions

LAYER	AVE. TEMP.	V. P. AT SATURATION	Δ V. P. EACH LAYER SATURATED	MAX. CAPACITY FOR EVAPORATION	SWEAT 538 GMS./M²/ HR. SUBJECT G. S.		SWEAT 193 GMS./M²/HR. SUBJECT J. S.		SWEAT 60 GMS./M²/HR. SUBJECT G. S.	
					Actual	Predicted	Actual	Predicted	Actual	Predicted
	°F.	mm. Hg	mm. Hg	gms./m²/hr.	gms./m²/hr.		gms./m²/hr.		gms./m²/hr.	
Skin	93	40			0	165	0	0	0	0
			16	373						
Undershirt	77	24			168	23	38	0	3	0
			15	350						
Shirt	50	9			88	233	32	76	4	0
			5	117						
Pile parka	25	4			122	70	73	70	23	13
			2	47						
Windbreak parka	6	2			31	24	23	24	16	24
			1	23						
Ambient air	0	1			101	23	24	23	14	23

outer layer will be condensed; it is immediately obvious that much more vapor can be transferred through the inner than through the outer layers.

In general this hypothesis seems to fit the findings in our three sample cases very well, and when there are discrepancies from the prediction there is usually a reasonable explanation. For example, when sweating was heavy (table 8, columns 5 and 6) it was predicted that 165 grams of moisture would be left on the skin. But it is likely that most of this would blot off into the undershirt and apparently that is what occurred. In this same experiment the actual sweat that reached the ambient air exceeded the prediction, but we know from experiments in which impermeable outer clothing was worn that subject G. S. sweats a good deal from the exposed portion of his face, and a fairly large part of the 101 grams that reached the ambient air was probably evaporated from the face. When sweating was moderate (columns 7 and 8) it was predicted that little would be retained in the inner layers, but that the amount in the outer layers would be about the same as in the experiment in which heavy sweating occurred; such was the case. Also in accordance with expectations, when sweating was light (columns 9 and 10) only the outer layers picked up moisture.

The hypothesis may be tested in at least two other ways. In figures 4 and 5 the final disposition of sweat in the series of experiments in which the grade of work was varied is shown. As heat production and sweating increased under these conditions we expected and found *a*, that loss of sweat to the ambient air reached a maximum first (except for sweat from the face), then *b*, that moisture uptake of the outer and middle layers approached constant maximal values beginning with the outer layer and working inward; also, *c*, that no moisture was retained in the inner layers when sweating was light, but that *d*, these inner layers became the only reservoir for the extra sweat secreted at the harder grades of work.

It is clear from this analysis that under these conditions a man can hope to be rid of his sweat as fast as it is produced only when he is sweating at an insensible level, and then only after adsorption of moisture by the cool outer layers of fabric has proceeded to equilibrium. Actually in several two-hour exposures at the lowest levels of activity moisture adsorption of the outer garments apparently exceeded insensible sweating, suggesting that some moisture was taken from the ambient air.

The explanation for the rapid drying of the inner clothing after a bout of profuse sweating is also implicit in this analysis. Since the underwear stays relatively warm, vapor pressures remain favorable for rapid evaporation of moisture from this layer, much of which will continue to be condensed on the outer layers of clothing.

The hypothesis will also explain the difference in the fate of equivalent amounts of sweat secreted at higher and lower temperatures than 0°F. (table 7). At higher ambient temperatures the flat portion of the vapor pressure curve is avoided with the result that potential vapor pressure differences may be greater between the outermost layers, facilitating evaporation of a substantially greater amount of moisture to the ambient air. However, the vapor pressure gradient between the inner layers may be sufficiently reduced, because of the narrowing of the range of temperatures of the layers of clothing, to increase condensation of moisture in them when heavy sweating occurs.

Efficiency of sweat for skin cooling. The effectiveness of sweat for skin cooling depends on its fate. If evaporated from the skin and transferred as vapor to the ambient air we may consider that about 0.58 Calorie were taken from the skin for each gram of sweat, and that the efficiency of the sweat was 100 per cent. But what was the efficiency in these experiments for the sweat that was left in the clothing?

If the hypothesis outlined in the preceding section regarding moisture transfer through clothing is accepted then the efficiency may be readily calculated because the inferences of that hypothesis are clear. Practically speaking we may consider *a*, that most of the sweat remaining in the underwear must have been blotted up from the skin as a result of the fact that the rate of sweating exceeded the capacity for evaporation from the skin at the existing vapor pressure gradient; and *b*, that any sweat retained in the intermediate and outer layers was condensed there after being evaporated from the skin.

In the process of condensation 0.58 Calorie per gram is given up. The principles governing the effectiveness of this heat of condensation for warming the skin are the same as for the effectiveness of electrical heat applied in clothing. A. C. Burton (1941) derived a statement of this effectiveness as follows: Let the insulation worn inside the point of heat supply (condensation) be I_1, that provided by the clothing and air outside the supply be I_2. Let the heat supplied at the point of condensation be H_1; the temperature of the skin, T_s; the temperature at the point where the heat of condensation is supplied, T; the temperature of the air, T_a. Then according to the fundamental equation for heat flow the flow of body heat, H, up to the region of temperature T is

$$K(T_s - T) = H \times I_1$$

while for the flow from the region of temperature T to the ambient air

$$K(T - T_a) = (H + H_1) \times I_2$$

Adding and rearranging

$$K(T_s - T_a) = \left(H + H_1 \frac{I_2}{I_1 + I_2}\right)(I_1 + I_2)$$

Thus the fraction of the heat, H, which affects the body is $\frac{I_2}{I_1 + I_2}$. Then the heat of condensation effective for rewarming the skin equals (total heat of condensation) $\times$

$$\frac{\text{insulation (clothing + air) outside point of condensation}}{\text{total insulation (clothing + air)}}$$

To take an example, any condensation that occurs two-thirds of the way out from the skin through the insulation is one-third effective for warming the skin. This means that a gram of water evaporated at the skin and recondensed two-thirds of the way out through the insulation has a net effectiveness for skin cooling of two-thirds of a gram.

In the light of the above considerations the net effective sweat has been calculated simply as total sweat minus net condensate effective for body warming. To simplify the computation of the efficiency of condensation the articles of clothing have been separated into four layers, and efficiencies have been assigned as follows:

Layer	*Components*	*Efficiency of condensation*
A	Thermocouple harness, cotton shorts, undershirt, underdrawers, cushion-sole socks, wool mitts	100%
C	Wool shirt, wool trousers, ski socks	70%
E	Pile parka	50%
G	Cotton parka, cotton trousers, shell mitts felt shoes	30%

By the simple device of treating moisture picked up in the inner layer, A, as condensate 100 per cent effective in recontributing heat to the skin we obtain a result (indicating 0 per cent efficiency of evaporation) that is consistent with the hypothesis that moisture which remained in the underwear was blotted up from the skin.

Net effective sweat has been calculated for the experiments in which grade of activity was varied and is plotted in figures 1 and 2. Net efficiency for body cooling of the sweat secreted obtained by dividing net effective sweat by total sweat amounted to as much as 65 to 75 per cent at levels of sweat production between 50 and 200 grams in two hours. However, as sweat production increased above about 200 grams the efficiency for cooling declined to less than 40 per cent at the highest levels of production. This relationship between amount of sweating and efficiency of sweating was expected from the previous analysis which showed that when sweating was light a larger fraction reached the ambient air and a larger fraction recondensed in the outer garments where efficiency for rewarming the skin was low.

When sweating was maintained at two levels at each of three different environmental temperatures net efficiency was greatest at 40°F., intermediate at 0°F., and least at −20°F. Here also the efficiency was less when sweating was heavier, as is shown in this summary of data from table 7:

Temperature °F.	*Average sweat 466 grams/two hours*	*Average sweat 851 grams/two hours*
+40	57%	54%
0	54%	43%
−20	47%	37%

It is conceivable that sweat might also accelerate heat loss from the body by increasing the conductivity of the clothing. The importance of this is suggested by the results of a study in which an electrically heated copper foot was dressed with three layers of woolen socks to which known amounts of water had been added. In these experiments evaporation was kept at a minimum by placing an impermeable rubber sock over the outer fabric sock and by keeping the temperature gradient from the skin to the ambient air relatively low. A concentration of moisture equal to 5 per cent of the weight of the socks then increased the conductivity of the sock assembly by about 14 per cent while moisture equal to 10 per cent of the sock weight increased conductivity about 26 per cent. If it is assumed that equivalent concentrations of moisture have about the same effect on conductivity of the Arctic Uniform the effect would be to raise the heat lost through the clothing from 1 to 25 per cent depending on the amount of moisture taken up. On this basis, when our subjects sweated 500 grams per hour at 0°F., heat loss due to increased conductivity was estimated at 13 Calories per hour while effective loss of heat by vaporization of the sweat amounted to about 125 Calories per hour. In most of these short exposures it is probable that heat loss due to moisture in the clothing was unimportant. It would be far more important during rest after a period of sweating, or when the clothing became really wet after several days of exposure.

SUMMARY AND CONCLUSIONS

Men dressed in an Arctic Uniform have been exposed to several degrees of cold while performing various levels of activity. Data were obtained on sweating, moisture uptake of the clothing, energy expenditure, pulmonary ventilation, skin temperature, rectal temperature and comfort.

The sweating of different subjects while performing the same hard work in the same clothing and at the same temperature varied widely, between about 350 and 725 grams per hour. The subjects who sweated more, generally had higher skin and rectal temperatures as well as higher pulse rates and greater energy production.

The week-to-week variability of values obtained on any one individual was small except as regards sweating, for which the coefficient of variability was about 11 per cent.

During experiments at temperatures between 40° and −40°F. most of the sweat secreted was taken up by the clothing; a larger proportion was taken up at the lower temperatures. When sweating was moderate the uptake was confined to the outer layers, but when profuse the underclothing was soaked. A hypothesis was formulated to explain the principles governing the behavior of the sweat and was found to be tenable for the data. According to this hypothesis the transfer of sweat from the skin does not depend on the over-all difference in vapor pressure between the skin and ambient air; it does depend *a*, on the vapor pressure difference from layer to layer in the system consisting of skin, clothing layers and ambient air, and *b*, on the specific resistance to vapor transfer provided by the fabrics and the air trapped in the clothing. Because the vapor pressure difference between the relatively warm inner layers and the cool outer layers is large there is little tendency to pick up moisture unless sweating is profuse; however, the vapor pressure difference between the cool outer layers and the environment is small with the result that much of the sweat secreted accumulates in the outer garments.

Based on the above hypothesis a method was evolved for determining the net sweating efficiency while a man is dressed. Sweating was shown to be an inefficient way to achieve body cooling when men are heavily dressed in the cold because much of the sweat originally evaporated at the skin is recondensed in the clothing giving back a portion of the heat of condensation to the skin. The amount of heat recontributed was shown to be proportional to a ratio obtained by dividing the amount of insulation lying outside the point of condensation by the total insulation. During walks at 0°F., the net sweating efficiency was greatest (between 60 and 75 per cent) at low rates of sweat production and least (40 per cent or less) when sweating was profuse.

The data suggest that when it is possible for men to modify their activity to the point of feeling "cool but comfortable" during Arctic exposures sweating and accumulation of moisture in the clothing will be minimal.

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